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The effect of grain drift on the structure of (Post–) AGB winds

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Abstract. We have developed an implementation for the momentum transfer force in numerical two fluid hydrodynamics. This form of the frictional coupling between gas and grains is consistent with the microscopic interactions between the two components. The coupling force gives rise to a drift velocity of the grains with respect to the gas. We apply this mechanism to the outflow of (Post-) AGB objects. Our numerical hydrodynamics code calculates self consistently the dynamics of these outflows, as well as the nucleation and growth of grains and equilibrium chemistry of the gas. Grain nucleation and growth are processes that depend strongly on the rate of gas–grain collisions. Hence, the drift velocity becomes an important variable. The tight connection between grain chemistry and drift causes the system to become extremely sensitive to small changes in almost any parameter. This may be a cause for deviation from (spherical) symmetry and structure.

1. Dust driven winds

Dust driven winds are powered by a fascinating interplay of radiation, chemical reactions, stellar pulsations and atmospheric dynamics. As soon as an AGB star's atmosphere develops sites suitable for the formation of solid "dust" (i.e. sites with a relatively high density and a low temperature) its dynamics will be dominated by the power of the radiative force. Dust grains absorb stellar radiation efficiently and experience a large radiation pressure. The momentum thus acquired is partially transferred to the ambient gas by frequent collisions. The gas is then blown outward in a dense, slow wind that can reach high mass loss rates.

2. Numerical hydrocode

We have written a numerical hydrodynamics code that self consistently calculates a dust driven wind. In our code both gas and dust are described by their own set of hydro equations (continuity, momentum). Exchange of matter (nucleation and growth of grains) and momentum (collisions) are taken into account in the source terms. The time dependent continuity and momentum equations are numerically solved using a two–step FCT/LCD algorithm (Boris 1976; Icke 1991). The abundances of H, H_2, C, C_2, C_2H, C_2H_2 and CO in the gas are calculated using a simple equilibrium chemistry (Dominik et al. 1990). Nucleation

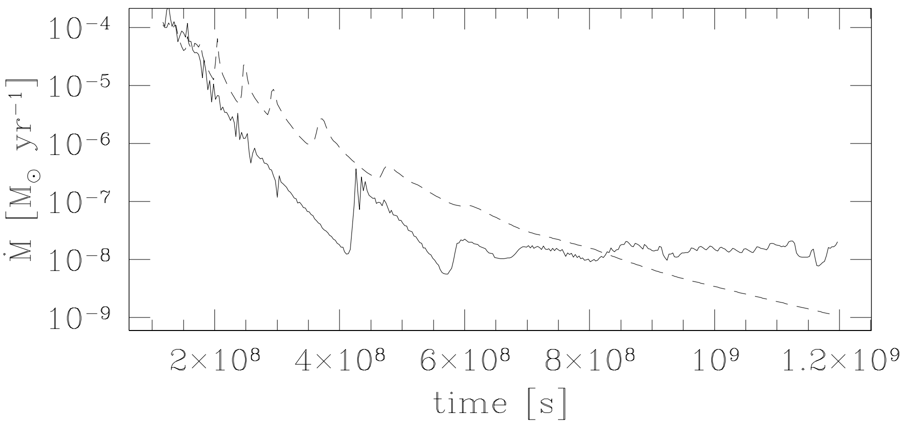

Figure 1. Mass loss rates for thermal (dashed line) and drift driven grain chemistry.

and growth of dust grains is described by the moment method (Gail, Keller, & Sedlmayr 1984; Gail & Sedlmayr 1988; Dorfi & Höfner 1991).

3. Two fluid hydrodynamics

Two fluid hydrodynamics requires a careful implementation of the momentum transfer term in terms of the drift velocity of the grains with respect to the gas. It turns out that the expression for this drag force that has been used before (e.g. Dominik 1992; Berruyer 1991; Krüger, Gauger, & Sedlmayr 1994) doesn't always apply, in particular when or where grains have just started to form. Moreover this expression just takes into account what we will call the "macroscopic" component of the drift velocity and doesn't incorporate the contribution to the momentum transfer due to the radiative acceleration between two subsequent collisions of a grain ("microscopic drift"). We have derived a new implementation for the momentum transfer from dust to gas, see Simis, Icke, & Dominik (2000):

$$f_{\rm drag} = n_{\rm d} g_{\rm rad} \frac{m_{\rm g}}{m_{\rm g}+m_{\rm d}} \left(1 + \frac{v}{\sqrt{v^2 + 2\lambda g_{\rm rad}} - v}\right) \tag{1}$$

Here, $n_{\rm d}$ is the number density of grains, $m_{\rm d,g}$ is the mass of a dust/gas particle, $\rho_{\rm d,g}$ are mass densities, $g_{\rm rad}$ is the radiative acceleration of a grain, $v = v_{\rm d} - v_{\rm g}$ is the drift velocity, λ is the mean free path of a grain and $\Omega = \rho_{\rm g} m_{\rm d} - \rho_{\rm d} m_{\rm g}/\rho_{\rm g}(m_{\rm g}+m_{\rm d})$. This expression takes into account the contribution of the radiative acceleration between individual gas–grain encounters as well. Especially when the mean free path of the grains is large, this radiation pressure contribution is important and may be the dominant factor in the momentum transfer. The equilibrium drift velocity corresponding to Eq. (1) is (Simis et al. 2000)

$$v_{\rm eq} = \sqrt{\frac{\Omega^2}{1-\Omega^2} 2\lambda g_{\rm rad}} \tag{2}$$

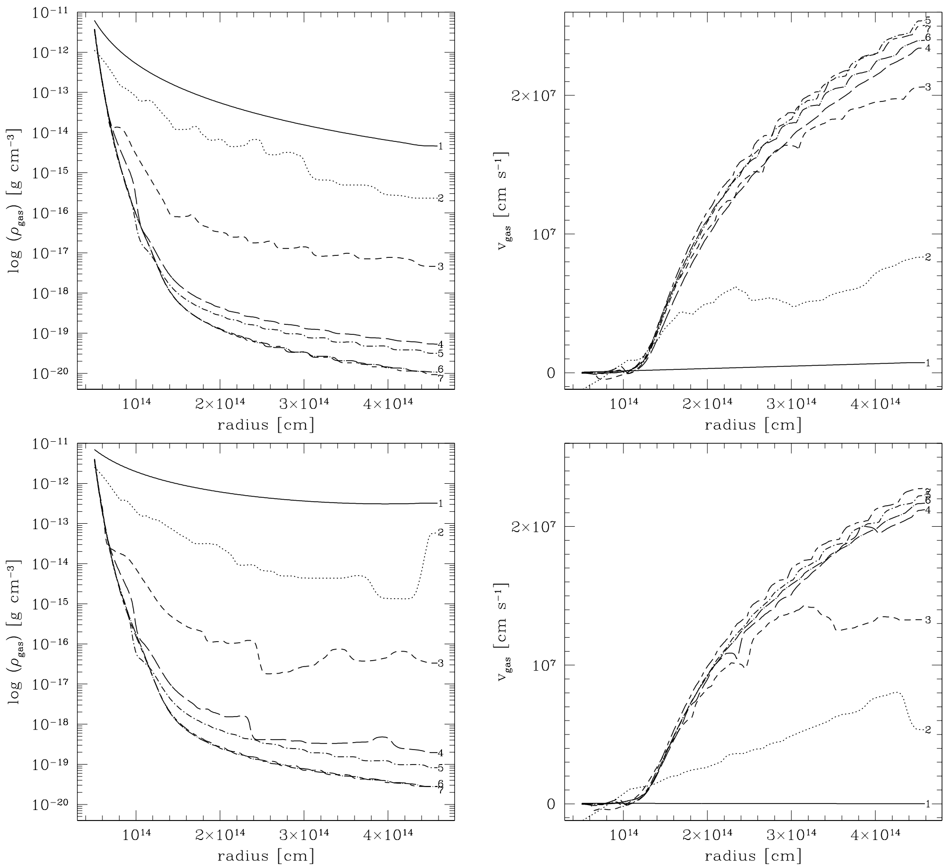

Figure 2. Density and velocity structure of simulated polar (upper two plots) and equatorial (lower two plots) outflow. Time after start of the wind is $0.0s$ (1), $0.57 \times 10^8 s$ (2), $2.07 \times 10^8 s$ (3), $3.57 \times 10^8 s$ (4), $5.07 \times 10^8 s$ (5), $6.57 \times 10^8 s$ (6), $8.07 \times 10^8 s$ (7)

This formalism will in the future allow to treat the coupling force also at non–equilibrium drift speeds. For the current calculations we have still assumed that the grains reach equilibrium speed quickly enough for the rate of momentum transfer to be given by $v = v_{\rm eq}$, i.e.

$$f_{\rm drag} = n_{\rm d} g_{\rm rad} \frac{\rho_{\rm g}}{\rho_{\rm g} + \rho_{\rm d}} \tag{3}$$

4. The effect of drift on the dynamics of the wind

The rates of grain nucleation and growth depend on the velocity with which grains and gas particles collide. In absence of drift, gas–grain collisions are thermally driven. Now that we have an expression for the drift velocity that is consistent with the micro–dynamics we can take into account the effect of drift on grain nucleation and growth. Since the drift velocity, through the radiation

pressure, depends on the number density and size spectrum of the grains we are now dealing with a very strong coupling between the dynamics and the chemistry rates in the outflow. When drift is taken into account, and in absence of sputtering, grains become bigger and more abundant than in the case when only thermal collisions are considered. In the case of drift driven grain chemistry, a wind with a terminal velocity and a mass loss rate that fluctuate around a constant value establishes itself. In the case of purely thermally driven grain chemistry, the gas outflow velocity and mass loss rate keep decreasing. At the same time dust continues to flow out at a high rate. This is illustrated in Figure 1, in which the mass loss history of an object with $M_* = 1M_\odot$, $T_* = 2200\ K$, $L_* = 1.0 \times 10^4 L_\odot$ and $\epsilon_C/\epsilon_O = 2$ is shown.

Due to the strong coupling of chemistry and dynamics, a small change in the parameters or flow variables may result in large changes in the flow. To illustrate this, we compare the outflows of a non–rotating object and an object with a rotation period of 50 years. The non–rotating object may be interpreted to represent the outflow in the polar direction and the rotating object to represent the outflow in the equatorial plane of an AGB star with a 50 year rotation period. The rotation is simulated by suitable adjustment of the effective gravity. Figure 2 shows the dynamical evolution of the density and velocity structure of the outflows. It turns out that the mass loss rate in the equatorial plane is twice the mass loss rate in the polar direction. The velocity in the polar direction is higher and the density is lower than in the equatorial plane. One may conclude that this zeroth order model of a rotating AGB object indicates that the initial polar to equatorial density gradient gives rise to a significant difference in mass loss rate, which may lead to a disk like structure. More generally this illustrates the tight coupling between dynamics and chemistry.

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